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Machining of Additively Manufactured Parts: Implications for Surface Integrity

Olusola Oyelola[a], Peter Crawforth[b], Rachid M'Saoubi[c], Adam T. Clare [a]*

[a]Advanced Component Engineering Laboratory, Faculty of Engineering, The University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[b]Advanced Manufacturing Research Center, University of Sheffield , Rotherham, S60 5TZ, UK
[c]Seco Tools (U.K) Ltd., Springfield Business Park , Alcester, Warwickshire, B49 6PU , UK

* Corresponding author. Tel.: +44 (0) 115 951 4109; Fax: +44 (0) 115 951 3800. *E-mail address:* adam.clare@nottingham.ac.uk

Abstract

Additive manufacturing methods continue to move towards production ready technologies with the widely extolled virtues of rapid transition from design to part and enhanced design freedoms. However, due to fundamental limitations of laser based processes for metal additive manufacturing, there is a significant ongoing need for these parts to be subject to additional machining operations. This paper reports on a study to investigate the machining behavior and surface integrity of Ti-6Al-4V components which have been produced by direct metal deposition using wire feedstocks. Simple geometries are produced and the resulting effect of tooling type is reported. Inhomogeneities in the deposition process as a result of non-uniform cooling and porosity are shown to have a deleterious effect on the surface integrity of the resulting part and the machinability of such components. In addition, strategies for the machining of AM parts which consist of graduated material structures are also proposed here.

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Keywords: Additive Manufacturing; Machining; Titanium, Microstructure

Introduction

Laser deposition is widely used in the manufacture and repair of metallic parts. The process provides a means for components of intricate geometry and desired properties to be manufactured through the use of a laser beam with material being delivered into the laser path on the desired substrate [1]. A number of factors including; alloying control, surface finish requirements and engineering tolerances mean most additive manufacturing techniques are only capable of producing near net shape components. There is often a need for further processing of Additive Manufacturing (AM) parts, therefore finish machining of such components has become imperative to satisfy these requirements. This has led to the development of hybrid systems capable of both building a part and machining the component to a suitable finish within the same work enclosure. This has been used to good effect for new part manufacture and part repair [2,3,4]. Reduction of material wastage is also a key driver in the use of AM, thus the need for post processing through subtractive methods should also be minimised.

Ti-6Al-4V is presently the most widely used titanium alloy and is commonly sought by a majority of metal AM users. Its use accounts for 50% of titanium tonnage in the world [5].The (α)-(β) microstructure of this alloy allows for high strength and formability. Laser cladding of Ti-6Al-4V in wire feedstock and powder form has been successfully undertaken by various authors [6,7,8]. Laser clad Ti-6Al-4V has also been reported to show a grain morphology differing from conventional cast Ti-6Al-4V as a result of the cooling process it undergoes. Solidification and cooling during the laser deposition process is rapid due to the thermal differential between the melt-pool and the previously solidified material/substrate [9]. Thus, for laser deposited Ti-6Al-4V, a Widmanstatten or martensitic structure (columnar growth) has been reported [10], whilst metal-mold cast Ti-6Al-4V form an equiaxed prior grain beta morphology [11].

Titanium and its alloys have been widely regarded as rather difficult to machine materials due to their highly reactive nature, low thermal conductivity, the relatively low modulus

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of elasticity and ability to retain hardness at high temperatures [12]. During machining, titanium alloys tend to weld to the cutting tool –formation of a built up edge (BUE); this consequently leads to tool chipping and consequently, shorter tool life. The low thermal conductivity property also adversely affects tool life as the temperature at the tool-workpiece interface remains elevated due to the heat generated not being transmitted through the workpiece or with the chips generated but rather through the tool. In machining operations such as grinding, even with the use of proper process parameters and conditions, there is a high susceptibility to reduction of fatigue strength due to surface damage [13] such as micro cracks, plastic deformation amongst others.
The purpose of this work is to investigate the changes in microstructure and thus properties after additively manufactured Titanium alloy is machined using two different tool types, since material properties are distinct and variable when compared to conventionally produced feedstocks. Knowledge of this aids in the design of the laser processing stage and also in the decisions on how best to carry out the post processing steps when required.
In the machining of Ti-6Al-4V, as with the properties of other titanium alloys, low cutting speed and high coolant pressure is necessary to achieve superior results due to the properties highlighted above. Other authors have demonstrated the use of various inserts with varying combination of feed and depth of cut with low cutting speeds [14,15] which have informed the parameters and conditions used in this study.

Experimental

In the Direct Metal Deposition (DMD) process used here, a 1.2mm diameter Ti-6Al-4V wire is used as the feedstock material. The wire is fed into a laser beam defocused to produce a beam spot diameter of 3.1mm. A 5mm thick Ti alloy plate was used as the substrate. The set-up was shielded in an Argon enclosure to prevent oxidation of the resulting deposits. These were also allowed to cool under this condition. To adequately mimic an industrial application of the process and with the post process machining process in mind, a circular first layer was built with optimum process parameters obtained from a previous study [8]. Subsequent passes with the relevant step up heights were made on the initial circular base produced. The resulting cylinder has an internal diameter of 70 ±0.5mm and an external diameter of 73 ±0.5mm with wall thickness 2.7±0.5mm and height of 61.7±0.5mm.

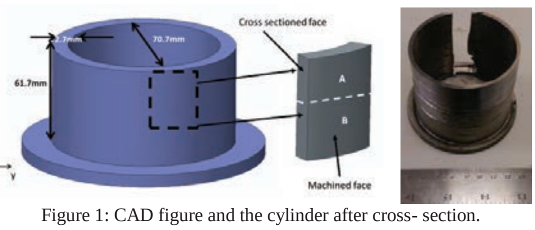

Figure 1: CAD figure and the cylinder after cross- section.

The cylinder was thereafter subjected to outside diameter turning operations. Two different inserts were used in machining two regions of the cylinder. The objective being to determine the effects of using coated and uncoated inserts on the workpiece generated. Both operations were carried out using identical machining parameters (shown in table 1). The coated insert was a PVD TiAlN based coated cemented carbide grade TS2000 with geometry: ISO CNMG120408-MF1. The uncoated insert had the same specifications and tool geometry. In both operations, coolant (HOCUT 795B) was delivered at a rate of 13 litres / min.
The two areas are referred to as ''A'' for the region with the uncoated tool and ''B'' for the region machined with the coated tool.

Table 1: Turning operation parameters.

Cutting Speed	70m / min
Feed Rate	0.15mm/ rev
Depth of Cut	1.25mm

Results

Metallurgical analysis of the clads showed two distinct microstructures within the clads. The structures observed coincided with the clad periphery (zone of re-melting) and within the clad itself. The structures were predominantly Widmanstatten patterns with varying degree of coarseness. The re-melted regions had larger grain size due to the effect of re-melting- this corresponds to a Widmanstatten α morphology. The other regions was however a basket weave Widmanstatten structure without the α segregation.

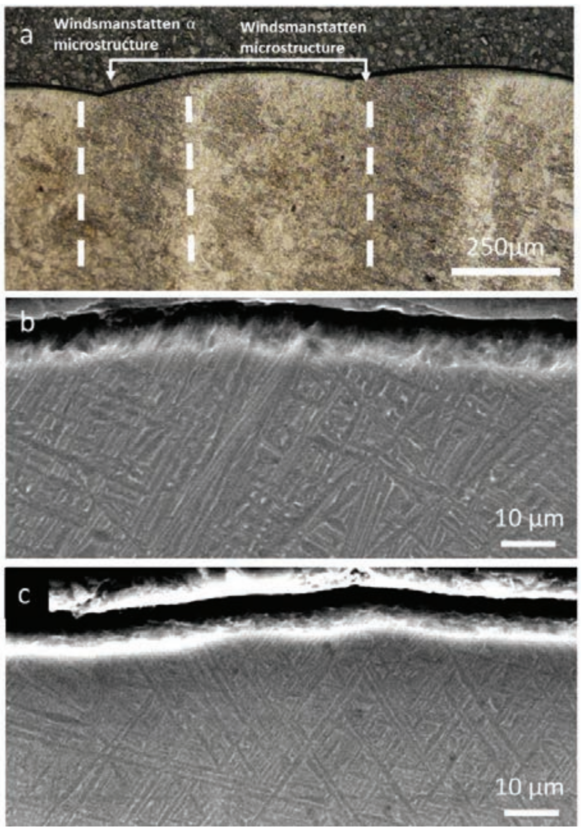

Figure 2:(a) Profile without machining showing variable microstructure,(b) region machined with a coated insert(c) region machined with a uncoated insert.

The regions between clads would be expected to show elevated hardness figures due to their more coarse micro structures and the tendency for work hardening within these regions. These regions retained their structure after the machining process as the transus temperature was not reached. It is anticipated that the difference in microstructures within this region might lead to a variation in cutting force requirements during machining. The effect of this on the cutting tool is also thought to be significant in extended use but does not form part of this study. After machining, the microstructure at the interface (Figures 2b and 2c), remains largely consistent.

Surface Roughness

A white light interferometer was used in determining the surface topography generated by the turning operation. The resulting plots are shown in Figure 2. Surface roughness values of 2.140 µm and 0.822 µm were obtained in the uncoated and coated regions accordingly. Surface Roughness is dependent on the process parameters and also the tool-workpiece combination. Since the resistance of the surface layer of the workpiece to deformation determines the actual contact area between the chip and tool face, it is believed this is more pronounced in the use of the uncoated tool as the tool is made of a less abrasive resistant material than the coating, hence the larger difference in gradient between the peak and the trough as shown in the Figure 3a.

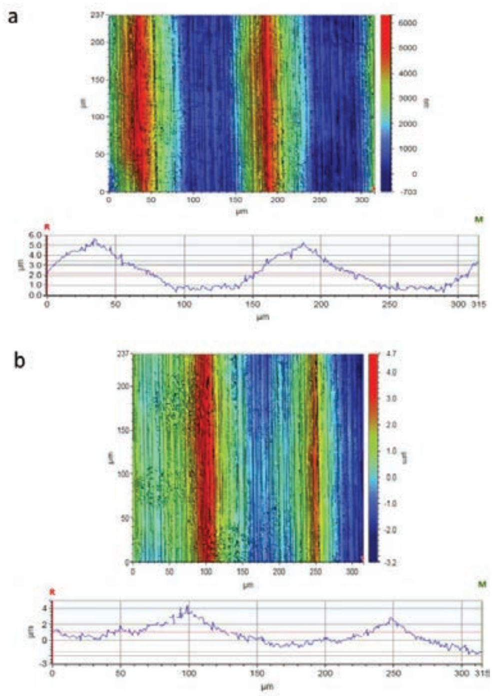

Figure 3: (a) Region machined with the uncoated insert (b) Region machined with the coated insert

Hardness

Hardness values obtained from a sample which was not machined showed slight variations in hardness within the build and the remelted regions. The remelted zone which has a similar structure to the area between clads, has an average hardness value of 338 HV. Post processed regions (at the top surface of the structures) show average hardness of 343 HV in Sample ‘A’ and 349HV in Sample ‘B’. The observed difference is due to effects of work hardening at the surface. The effects of the inserts in elevating the hardness was however similar as they produced similar results in both regions.

Chip Formation

Ti-6Al-4V produces shear localised segmented chips during machining. The contact length on the rake surface is often limited to 1-2 segments resulting in higher stress on the cutting tool and premature tool failure. In this study, both regions produced characteristically long ‘stringy’ chips.

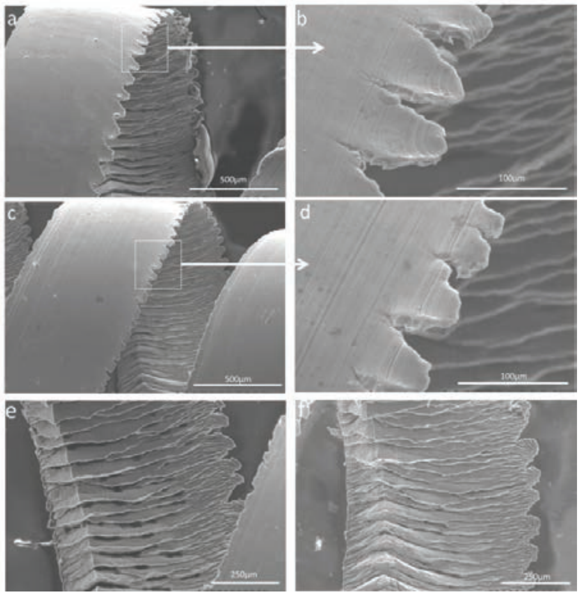

Figure 4: (**a**) Region A –Uncoated insert region, (**b**) Higher magnification of highlighted region in (a), (**c**) Region B - (Coated insert region), (**d**) Higher magnification of highlighted region in (c), (**e**) Chip structure of A (**f**) Chip structure in B

The region machined with the uncoated insert (Region A) had more uneven chip geometry with widely varying pitch between successive crests of the chips. Region B had chips that are regular with periodicity in their patterns, pointing to a more stable process of deformation in the workpiece. This region also shows relatively thinner bands in chip geometry. Chips from B showed rounder peaks, which implies cyclic movements of the tool tip due to the dynamic nature of the chip formation process during machining.

Region A exhibited chips with a more of a pronounced saw tooth profile. The mechanism of this chip formation process- typical of low-thermal diffusivity materials such as titanium alloys- has been attributed to a flow localisation process involving the creation of a plastic instability and shearing along localised deformation bands [16]. The periodicity of this phenomenon is also reflected in the topography of the machined surface displaying more undulations than what would be expected from a continuous chip formation process.

Residual Stress

Multi-layer additive manufacturing has been reported to induce residual stresses due the rapid cooling and solidification materials undergo. According to Capello [17], during machining operations, tensile residual stresses are caused by thermal effects whilst compressive stresses are due to the action of the cutting tool. The region directly in front of the tool experiences a rise in the compressive plastic deformation and the regions just after the tool tip experiences tensile plastic deformation. The final residual stress state distribution of the workpiece is determined by the magnitude of these forces [18].

X-ray diffraction was used in the determination of the residual stresses induced in the workpiece. Stress measurements carried out as a series of 2θ scans from 137º to 147º (α-Ti-(213) peak), step size 0.1º and step time 20 s. The scans were collected with the sample side-tilted to 10 evenly spaced $\sin^2\psi$ values from 0.00 to 0.75, in two measurement directions, φ 0° (parallel to the length) and 90°(parallel to the circumference). Diffraction scans were processed by background subtraction, Lorentz-polarization correction, smoothing, and $K\alpha_2$ subtraction. Peak positions were calculated by averaging gravity centres above intensity thresholds from 25% to 75% in steps of 5%. Stress was calculated from the gradient of the relationship between d and $\sin^2\psi$ using a linear fit (biaxial stress), and elastic constant (E/ (1+ν)) of ~84 GPa [19].

Residual stresses in both regions appear to be compressive with varying values in the axial and circumferential directions. The region machined with the uncoated insert (A) had compressive stresses values of ~246 MPa (SD=41.14) and ~413MPa (SD=33) in both directions (0° and 90°) respectively. The region machined with the coated insert (B) had values of ~171 MPa (SD=54) and ~520 MPa (SD=38). In comparing these values, it is inferred the ratio between values in the sample machined with the coated sample 'B' had higher residual compressive stresses. This is related to the thermal events associated with the formation of chips and the interactions between the tool cutting edge and the machined surface in the region.

Conclusions

Additively manufactured Titanium alloy (Ti-6Al-4V) has been machined in this study with the effects of using two different tool inserts with the same operating conditions investigated.

- Compressive stresses are seen to be prevalent along the surface of the samples evaluated. The compressive stresses parallel to the circumference shows the sample machined with a coated insert had higher compressive stresses in this direction. It also shows a higher ratio when compared to the sample machined without the coating.

- For optimum machining, a control system which can adapt the cutting force requirement and conditions within the workpiece and relate this to the input is being proposed. This would be of particular importance and use in machining workpieces with randomly dispersed components and functionally graded components built with laser cladding processes**.**

- The role of varying microstructure in the AM part on machining is yet to be fully understood and requires further work

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